Why the HBT data are not in agreement with a single chemical and kinetic freeze-out

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Abstract

Based on simple scale arguments we argue that any thermalized fireball evolution scenario which is in agreement with the observed Hanbury-Brown Twiss (HBT) correlation radii at RHIC and reproduces the measured total multiplicity cannot reflect the distribution of matter at or close to a phase transition temperature of ~ 170 MeV and any scenario which assumes that HBT reflects these properties cannot be reached by a sensible choice of evolution parameters while agreeing with all correlation radii. We investigate this question in more detail using a parametrized version of the fireball evolution which has been shown to reproduce particle spectra and HBT for a separate chemical and kinetic freeze-out.

I. INTRODUCTION

The measurement of identical two particle correlations in heavy ion collisions is capable of providing a wealth of information about the phase space distribution of the emitting source created in the collision (for an overview see [1, 2]). It is commonly assumed that the experimentally accessible Hanbury-Brown Twiss correlation functions measure properties of the collision system at kinetic decoupling, i.e. the point of last interaction of the emitted particles. Assuming that the collision created a thermalized system and taking into account the measured one particle spectra of different particle species, essential scale parameters of the system at breakup can be extracted from the data by fitting a suitable parametrized emission source to both spectra and correlation functions. Examples of such studies are [3] for SPS and [4, 5] for RHIC conditions.

The crucial point in these studies is the following: Single particle spectra or HBT correlations alone depend on combinations of the temperature T and collective expansion velocity $\overline{v}$ of the emission source. Therefore, a model fitted to either HBT correlations or spectra can only determine possible pairs of $(T, \overline{v})$. However, the functional dependence of single-particle spectra and two-particle correlations on these parameters is different, therefore a simultaneous fit to both quantities is able to resolve this ambiguity [3].

Such studies find that kinetic decoupling temperatures less than 120 MeV are favoured by the data, significantly below the phase transition temperature $T_C \approx 170$ MeV. They imply a significant amount of interaction following the phase transition and consequently hadronic re-scattering cannot be neglected. On the other hand, statistical models are highly successful in describing the measured abundancies of hadrons and require hadrochemical freeze-out temperatures very close to T_C at full SPS and RHIC energies [6, 7]. These two observations give rise to the common picture of separate chemical and kinetic freeze-out.

In contrast, in a series of papers [8] a single freeze-out model has been proposed in which both hadron abundancies and momentum spectra are fixed at the phase transition and there are no significant scattering processes beyond this point.

A different suggestion has been made in [9, 10]. There it was argued that elastic rescattering processes do not affect the HBT correlation significantly and therefore the observed HBT parameters would not reflect properties of the system at kinetic decoupling but at the phase transition or the chemical freeze-out point where supposedly the last significant inelastic

scattering processes occur.

For SPS conditions there is good experimental evidence for substantial hadronic rescattering from the dilepton invariant mass spectrum. Dynamical models are unable to explain the enhancement of dilepton emission below the ρ mass seen in the CERES data [11] by a possible quark-gluon plasma (QGP) contribution [12, 13, 14, 15]. It is difficult to conceive how this region should be filled if vacuum properties of hadrons are relevant. In order for a hadronic contribution to describe the data, either a mass shift of the ρ or a strong broadening due to its interaction with a hot and dense medium is necessary.

It is the purpose of this letter to demonstrate that the measured HBT data [16] at RHIC cannot reflect properties of matter near T_C if some simple scale constraints are taken into account, thus giving evidence that there has to be substantial inelastic rescattering in the hadronic evolution below T_C if one assumes evolution in or close to thermal equilibrium. This result is in line with evidence from the simultaneous fits to spectra and HBT correlations and the independent evidence from dilepton emission at SPS mentioned above. It strongly supports the notion that the chemical freeze-out and the kinetic freeze-out do not occur at the same time.

II. SOME SCALE ARGUMENTS

HBT correlation measurements do not reveal the source geometry as such but rather measure regions of homogeneity. This can be easily seen in a simple calculation assuming a Gaussian source: Using this ansatz, for example the relation between the correlation radius R_{side} and the geometrical (Gaussian) radius of the source R_G is [1]

$$R_{side}(m_t) = \frac{R_G}{\sqrt{1 + m_t \eta_{\perp f}^2 / T_f}} \tag{1}$$

where we have introduced the source temperature at kinetic decoupling T_f, the transverse mass $m_t = \sqrt{m^2 + p_\perp^2}$ of the emitted particles and the transverse rapidity $\eta_{\perp f}$ at the Gaussian radius R_G as a measure of the transverse flow (assuming a linear increase of the transverse rapidity with radius r) at the breakup time.

Expressions assuming other density distributions and flow profiles are naturally different, however the essential physics is apparent from this particular example: In the limit of vanishing transverse mass, correlation radius and geometrical radius agree. For finite transverse

mass, the presence of strong flow (large $\eta_\perp$) tends to decrease the correlation radius by introducing a shift in the average momentum for two particles emitted from different spacetime points, whereas a large temperature tends to compensate for this effect by introducing a momentum spread for all particles emitted from a particular point. Thus, the falloff of the correlation parameter with m_t is governed by the ratio $\eta_\perp^2/T_f$. In particular, this implies that if a scenario with $T_f \approx 100$ MeV can describe the experimental data, the corresponding transverse flow in any scenario assuming a freeze-out temperature of 170 MeV has to be stronger in order to generate the same falloff in transverse mass.

Calculating the total entropy based on the observed multiplicity and with the help of an equation of state (EOS) based on quasiparticle degrees of freedom [17] or using directly the EOS as found in lattice QCD simulations at finite temperature (see e.g. [18], the difference between both approaches mainly being the value of the bare quark masses) we can estimate the volume occupied by hot matter produced in an Au-Au collision at full RHIC energy at T_C as about $V_{max} \sim 4500$ fm^3. This is an upper bound for the volume of the emission source seen in the HBT data — any larger volume will require more entropy than measured experimentally to contain matter at T_C.

In the following, we make some very rough estimates for the minimum source volume seen in the HBT data. We argue that for $T = T_C$ this volume has to be much larger than the upper bound V_{max} discussed above. A larger system with the experimentally determined entropy, however, must be cooler than 170 MeV, hence the measured HBT correlations cannot originate from matter at $T = T_C$.

Assuming cylindrical fireball geometry and Gaussian distributions of matter density in longitudinal and transverse direction, the Gaussian volume at breakup can roughly be estimated from the correlation radii as $V = (2\pi)^{3/2} R_{side}^2 R_{long}$. Here, the correlation radii have to be determined at $m_t = 0$. Experimentally this limit is not accessible, but we can obtain a lower limit by estimating the volume of the region of homogeneity for low transverse momenta by using the data in the smallest transverse momentum bin.

The simple Gaussian ansatz yields $R_{side} \approx 4.9$ fm, $R_{long} \approx 5.9$ fm and a volume of about 2250 fm^3. This seems to be in agreement with the value of V_{max} but misses out the necessary extrapolation to $m_t = 0$, so the true volume may well be larger than V_{max}.

In essence, this is a crude estimate, but the fact that the volume of the region of homogeneity is already of the order of magnitude of the maximum possible volume for matter at $T = T_C$

reveals that there is a constraint (in the following referred to as 'volume constraint') — if the flow in the evolution scenario is such that the region of homogeneity is only about half of the total fireball volume or less then the extrapolation to the true geometrical size of the emission source will yield a volume $V > V_{max}$ and the scenario is not compatible with the constraints set by thermodynamics.

There is yet another constraint: Again, for simplicity assuming Gaussian distributions of matter, the root mean square (rms) radius of the region of homogeneity estimated from the lowest momentum bin of R_{side} is about 7 fm (using $R_{rms} = \sqrt{2}R_G$), whereas the rms radius of the initial gold nucleus (averaged over the centrality bins for which the HBT correlations are measured) is ~ 4.6 fm. Thus, there is an increase in the rms radius of at least 2.4 fm visible in the data. In a thermal description of the fireball, transverse flow would be at the origin of the increase in radius and one should expect $v_\perp^{rms}(\tau) = a_\perp \tau$ and $R_{rms}(\tau) = R_{rms}^0 + a\tau^2/2$ (with R_{rms}^0 the initial rms radius as calculated in overlap calculations and $a_\perp$ the acceleration) to approximate the expansion. Once the amount of flow is specified (which can be done by using the one-particle momentum spectra), this yields a solution $(\tau, a_\perp)$ for the timescale of the transverse expansion. For a moderate flow of $v = 0.5c$, we find in our rough estimate $\tau = 9.6$ fm/c, for strong flow of $v = 0.8c$, we get $\tau = 6$ fm/c. However, during this time needed for the transverse expansion, the longitudinal expansion takes place as well. In a boost invariant scenario, the longitudinal extension of the system at time τ (measured in the thermodynamically relevant frames locally co-moving with the expanding matter) comes out as $2\eta_{max}\tau$. The experimentally observed rapidity interval of produced matter is $-\eta_{max} \sim -3.5 < \eta < 3.5 \sim \eta_{max}$. Using the estimate for the time given above and the measured η_{max} we find length scales of $L = 42(67)$ fm, well in excess of the length of the region of homogeneity estimated from the lowest momentum bin of the R_{long} data. Thus, during the time necessary for the observed radial expansion, the initial longitudinal motion of matter in a boost-invariant scenario leads to a large longitudinal extension which in turn implies a violation of the volume constraint (we refer to this as 'time constraint' in the following).

Since the rapidity distribution of matter is a measured quantity, this constraint cannot be avoided by a slower boost-invariant expansion. However, longitudinal stopping and re-acceleration as in the Landau scenario can lead to a significantly smaller longitudinal extension for a given expansion time τ while the same rapidity distribution can be achieved.

Thus a Bjorken expansion picture cannot possibly be reconciled with the assumption of a freeze-out at the phase transition; at least some degree of a Landau-type initial longitudinal compression and re-expansion of matter must be assumed in order to match the scales.

III. A DETAILED INVESTIGATION

In this section, we will investigate the rough estimates of the previous section using a model framework for the fireball expansion which in essence is a parametrization inspired by a hydrodynamical evolution of the collision system. This model has been shown to give a good description of both single particle spectra and two particle correlations at RHIC simultaneously for a breakup temperature well below the phase transition temperature. It is described in greater detail in [4], here we only repeat the essential facts:

For the entropy density at a given proper time we make the ansatz

$$s(\tau, \eta_s, r) = N R(r, \tau) \cdot H(\eta_s, \tau) \tag{2}$$

with τ the proper time measured in a frame co-moving with a given volume element, $\eta_s = \frac{1}{2} \ln(\frac{t+z}{t-z})$ the spacetime rapidity and $R(r, \tau), H(\eta_s, \tau)$ two functions describing the shape of the distribution and N a normalization factor. We use Woods-Saxon distributions

$$\begin{aligned}
R(r, \tau) &= 1/\left(1 + \exp\left[\frac{r - R_c(\tau)}{d_{\mathrm{ws}}}\right]\right) \\
H(\eta_s, \tau) &= 1/\left(1 + \exp\left[\frac{\eta_s - H_c(\tau)}{\eta_{\mathrm{ws}}}\right]\right).
\end{aligned} \tag{3}$$

for the shapes. Thus, the ingredients of the model are the skin thickness parameters d_{ws} and η_{ws} and the parametrizations of the expansion of the spatial extensions $R_c(\tau), H_c(\tau)$ as a function of proper time. From the distribution of entropy density, the thermodynamics can be inferred via the EoS and particle emission is then calculated using the Cooper-Frye formula. In [4], the model parameters have been adjusted such that the model gives a good description of the data.

It is the aim of the present letter to test how well a description of the HBT correlation measurements is possible if one assumes that the HBT measurement reflects the properties of matter at the phase transition, either because of a common chemical and thermal freeze-out of because elastic rescattering does not modify the correlations. The strategy is the following: Using a set of assumptions characterizing a given scenario, we will tune the

remaining parameters such that a good description of one HBT parameter is achieved and investigate how well the other correlation radii are reproduced by this choice.

For simplicity, we take the transverse acceleration $a_\perp$ to be a constant (i.e. independent of the EoS) and only fix the final value $v_\perp^{rms}$ at the rms radius of the fireball.
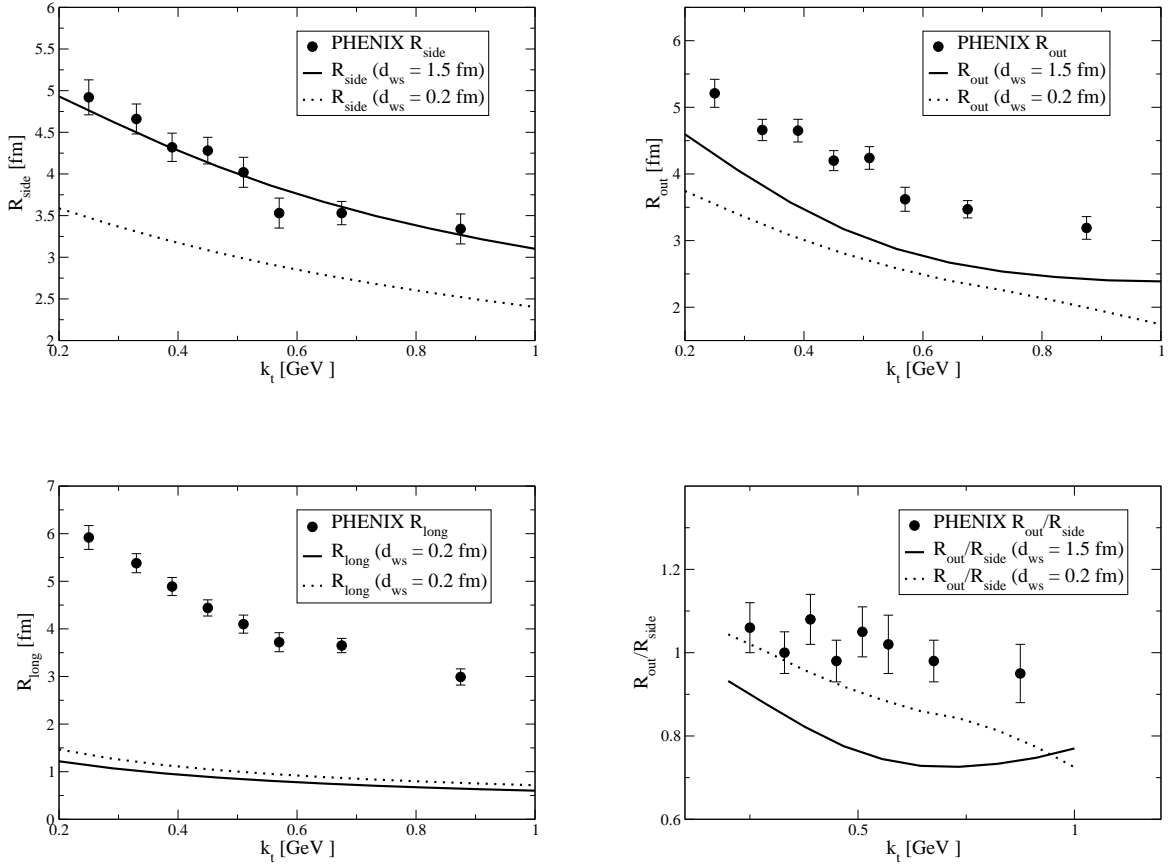
A. Strong longitudinal constraints

FIG. 1: The HBT correlation parameters $R_{\mathrm{side}}, R_{\mathrm{out}}, R_{\mathrm{long}}$ and the ratio $R_{\mathrm{out}}/R_{\mathrm{side}}$ in the model calculation as compared to PHENIX data [16], assuming almost complete initial compression of matter. Shown are the results corresponding to two different skin thickness parameters d_{ws} of the entropy density distribution.

In a first calculation, we assume that the fireball evolution incorporates a simultaneous chemical and kinetic freeze-out at the phase transition. This implies that the rapidity

interval filled by the matter at breakup has to agree with the experimentally observed rapidity interval, i.e. the emission source has to fill about 7 units of rapidity.

Assuming a Bjorken boost-invarinat non-accelerated expansion scenario, this strong longitudinal flow implies a quick volume expansion. Thus, the volume constraint is hit early before transverse flow could expand the system and no satisfactory description of R_{side} is possible since the geometrical radius ends up being smaller than the radius of the homogeneity region.

However, going to the opposite limit of almost completely stopped matter $(-0.2 < \eta_0 < 0.2)$ and accelerated re-expansion to the finally observed interval a good description of R_{side} is possible with a large surface thickness parameter $d_{ws} \sim 1.5$ fm and strong transverse flow $v_\perp^{rms} \approx 0.8$. This, however, is not caused by a dynamical expansion but by the fact that the highly compressed initial state in combination with the surface smearing leads to a huge initial temperature and a Cooper-Frye surface far away from the rms radius of the entropy density distribution. In fact, the hypersurface moves inward as the longitudinal acceleration leads to rapid cooling of the system in the later stages.

The resulting correlation radii are shown (for comparison also using a sharp surface with $d_{ws} = 0.2$ fm) in Fig. 1. The largest discrepancy is seen in R_{long}. It is evident that the system did not have enough time for longitudinal expansion such that the normalization of R_{long} could be reproduced. The falloff in m_t is however in agreement with the data (as can be seen by rescaling the curve with a constant factor) as it should since the scenario reproduces the experimentally observed rapidity interval. The normalization is off by a factor of ~ 4 which cannot easily be accounted for by a peculiarity of the present model.

B. Weak longitudinal constraints

Assuming that there are still elastic rescattering processes going after the phase transition, there's no reason why the rapidity interval filled by matter at the phase transition point should agree with the experimentally accessible rapidity interval which reflects properties of matter at the later kinetic freeze-out. If the HBT correlation radii would be unaffected by elastic rescatterings, the rapidity interval relevant for R_{long} would be that at the phase transition.

In principle, this would allow for longitudinal expansion slower than in the previous case,

leading to more transverse expansion and improving the agreement with the measured HBT radii. However, the falloff of R_{long} with m_t demands a longitudinal velocity gradient which is compatible with the measured rapidity interval. The only longitudinal ambiguity concerns the amount of initial longitudinal compression, and the relevant parameter η_0 can be fit to the absolute magnitude of R_{long}.

In doing so, however, it turns out that the absolute magnitude of R_{long} cannot be fitted even for vanishing transverse flow - the longitudinal expansion with the observed velocity gradient alone requires a volume which is not in agreement with the volume constraint — in spite of the correct falloff, the resulting curve is 20% below the data (and, having no transverse flow, the resulting scenario fits neither R_{side} nor the transverse mass spectra). This is apparent from Fig. 2.

The result is readily interpreted: A sharp surface of the radial density distribution leads to a stationary Cooper-Frye surface and hence to less emission before breakup than a dilute distribution which implies a receding Cooper-Frye surface. Thus, the system has a slightly longer lifetime for $d_{ws} = 0.2$ fm/c, leading to more expansion and a better description of R_{long}. On the other hand, a dilute distribution initially implies a Cooper-Frye surface farther out and hence a slightly larger R_{side}. The behaviour of R_{side} and R_{long} illustrates nicely the tradeoff between longitudinal and transverse extension caused by the volume constraint.

IV. SUMMARY

We have shown both by simple scale arguments and in more detailed studies that a freeze-out temperature of 170 MeV cannot be compatible with the measured data. Thus, the 2-particle correlations do not give any indication that there would be either a simultaneous chemical and kinetic freeze-out or that only elastic scattering processes which do not modify the HBT correlations prevail after the phase transition.

This is in essence due to the fact that the falloff of the HBT radii with transverse momentum requires a strong flow, even more so for a comparatively large temperature of 170 MeV. In the presence of strong flow however the region of homogeneity seen in the correlation parameters is smaller than the actual volume, hence the true geometrical volume necessary for these radii exceeds by far the volume determined by the EoS and the total fireball entropy.

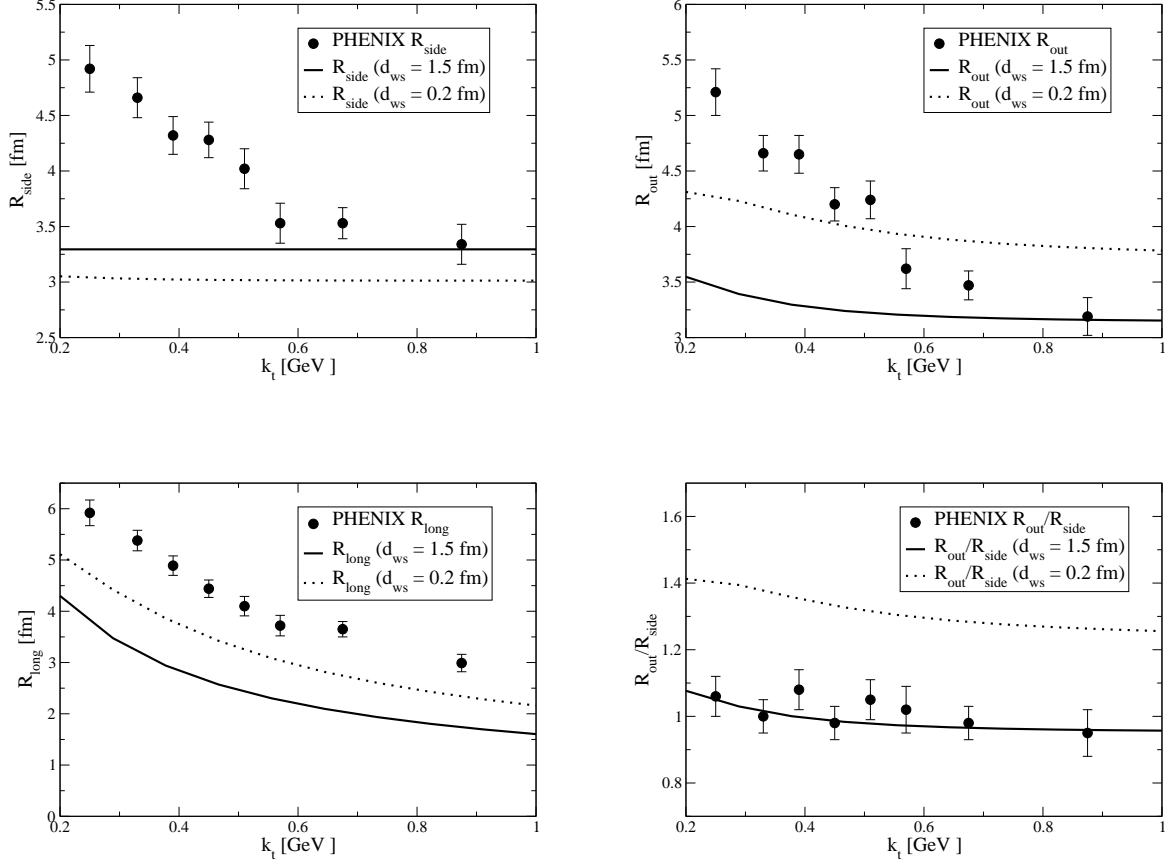This is not an artefact of the model - mismatches between calculation and data for the best

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FIG. 2: The HBT correlation parameters $R_{\mathrm{side}}, R_{\mathrm{out}}, R_{\mathrm{long}}$ and the ratio $R_{\mathrm{out}}/R_{\mathrm{side}}$ in the model calculation as compared to PHENIX data [16], aiming for the best possible description of R_{long} assuming vanishing transverse flow. Shown is the result corresponding to two different skin thickness parameters d_{ws} of the entropy density distribution.

choice of parameters of order 3-4 indicate that this is a fundamental problem. We have not even made an attempt to simultaneously describe single particle spectra for these emission temperature and flow combinations.

The logical conclusion is then that chemical and thermal freeze-out are separate phenomena and that the HBT correlation radii reflect indeed properties of matter at or close to the kinetic freeze-out temperature. This requires frequent interactions in the hadronic evolution phase and the production of resonance states, a conclusion which is directly confirmed in the SPS case by the measured dilepton invariant mass spectrum.

Acknowledgments

[1] U. A. Wiedemann and U. W. Heinz, Phys. Rept. **319** (1999) 145.

[2] B. Tomasik and U. A. Wiedemann, hep-ph/0210250.

[3] B. Tomasik, U. A. Wiedemann and U. W. Heinz, Heavy Ion Phys. **17** (2003) 105.

[4] T. Renk, hep-ph/0404140.

[5] F. Retiere and M. A. Lisa, nucl-th/0312024.

[6] P. Braun-Munzinger, J. Stachel and C. Wetterich, nucl-th/0311005.

[7] P. Braun-Munzinger, K. Redlich and J. Stachel in *Quark Gluon Plasma 3* (eds. R.C. Hwa and X. -N. Wang) (World Scientific Pub Co 2004).

[8] W. Broniowski and W. Florkowski, Phys. Rev. Lett. **87** (2001) 272302; Phys. Rev. C **65** (2002) 024905; W. Broniowski, A. Baran, and W. Florkowski, Acta Phys. Pol. B **33** (2002) 4235; A. Baran, W. Broniowski, and W. Florkowski, Acta Phys. Pol. B **35** (2004) 779.

[9] C. Y. Wong, hep-ph/0403025.

[10] C. Y. Wong, J. Phys. G **29**, 2151 (2003).

[11] G. Agakichiev et al., CERES collaboration, Phys. Rev. Lett. **75** (1995) 1272; G. Agakichiev et al., CERES collaboration, Phys. Lett. **B422** (1998) 405.

[12] R. Rapp and J. Wambach, Adv. Nucl. Phys. **25** (2000) 1.

[13] T. Renk, hep-ph/0403239.

[14] T. Renk and A. Mishra, Phys. Rev. C **69** (2004) 054905.

[15] T. Renk, R. A. Schneider and W. Weise, Phys. Rev. C **66** (2002) 014902.

[16] S. S. Adler *et al.* [PHENIX Collaboration], nucl-ex/0401003.

[17] R. A. Schneider and W. Weise, Phys. Rev. C **64** (2001) 055201; M. A. Thaler, R. A. Schneider and W. Weise, hep-ph/0310251.

[18] C. R. Allton, S. Ejiri, S. J. Hands, O. Kaczmarek, F. Karsch, E. Laermann and C. Schmidt,

Phys. Rev. D **68** (2003) 014507.